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RADIOACTIVE ION BEAM RESEARCH AT LLNL

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ABSTRACT

In this paper we discuss efforts underway at LLNL to develop the technology for the measurement of proton and alpha-particle reactions with unstable nuclei which are necessary for understanding the nucleosynthesis and energy generation in hot hydrogen-burning environments.

INTRODUCTION

Even after several decades of research[1] into the mechanisms by which the elements are synthesized in stars, it is still often true that the degree to which an astrophysical environment can be understood is limited by the degree to which the underlying microscopic input nuclear physics data have been measured and understood. As new and more exotic high-temperature astronomical environments have been discovered and modelled (and as observations and models for more familiar objects have been refined) the needs for more and better data for nuclei away from stability have increased. In this brief overview, we discuss the exotic environments for hot hydrogen burning and some of our experimental and theoretical efforts to obtain the desired nuclear data.

HOT HYDROGEN BURNING

Since the landmark work of Wallace and Woosley[2] it has been clear that hydrogen burning may occur at temperatures far in excess of the temperatures ($10^6 < T < 10^8$K) associated with the main-sequence evolution of normal stars for a host of astrophysical environments (see Fig. 1). In such environments, charged-particle reaction cross sections for unstable nuclei become particularly important.

Almost any time there is thermonuclear hydrogen burning, there is a possibility for proton reactions on unstable nuclei. Well known examples are the ^{7}Be(p,γ)^{8}B reaction in the sun (which is an important link in the chain of reactions leading to the production of solar neutrinos detectable in the ^{37}Cl experiment[3]), the ^{22}Na(p,γ)^{23}Mg reaction in the Ne-Na cycle, and the reactions of ^{26}Al in the Mg-Al cycle. When the temperatures are high, a few other reaction rates also become important. For $T \gtrsim 2\times10^8$K the waiting point for the normal hydrogen-burning CNO cycle shifts[4] from ^{14}N to ^{13}N, and then, via the ^{13}N(p,γ)^{14}O reaction, shifts to the production of ^{14}O and ^{15}O. This is the hot (beta-limited) CNO cycle[2], which is probably significant in the evolution of supermassive ($M > 10^4 M_\odot$) stars[5]. This hot hydrogen-burning scenario may also come into play on accreting white dwarfs[2] and in the formation of x-ray bursts from accreting neutron stars[6,7].

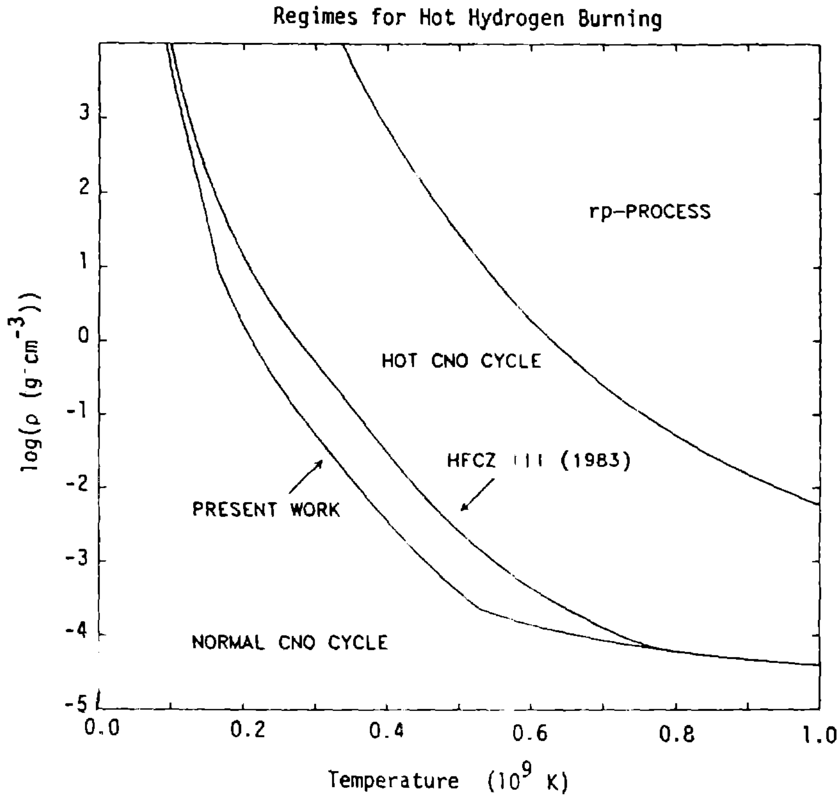


Figure 1 Regions of the density vs. temperature plane in which the various hydrogen-burning processes are dominant (from ref. 4). The normal CNO cycle occurs in stars slightly larger than the sun. The hot (beta-limited) CNO cycle is particularly important in supermassive stars. The rp-process is important during the thermonuclear runaways on accreting neutron stars which may be the source of X-ray bursts.

As the temperature and density continue to increase, the $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{15}O(\alpha,p)^{18}F$ reactions lead to a break out from the CNO cycle and eventually to a process of rapid proton capture. This rp-process involves sequential proton captures out to the proton drip line or until the Coulomb barrier becomes too large. Each of the transitions to higher-temperature reactions leads to orders-of-magnitude increases in the rates of energy production. Thus, in addition to the effects on nucleosynthesis, the dynamics of the various high-temperature environments are intimately coupled to the cross sections for proton and alpha-particle capture reactions on unstable nuclei.

Essentially two different approaches have been attempted to supply the nuclear data for these hot hydrogen-burning scenarios. The most straightforward approach (which we will call the finesse approach) is to utilize nuclear data obtained by conventional means combined with a model for the nuclear structure and reaction mechanisms to derive the desired input datum. This has been done for the $^{13}N(p,\gamma)^{14}O$ reaction[4,8,9], the ^{14}O, ^{15}O, and ^{19}Ne reactions[10] and heavier nuclei[11]. This approach has been quite productive since many of the reactions of interest are probably dominated by one or a few resonances whose radiative and particle widths can be inferred indirectly. There is still quite a bit that can be done with this approach, for example to better identify the energies and widths of the resonances of interest. The problem with this approach, however, is that one can never be quite sure that enough physics and input data have been included in the calculations to be confident that the inferred cross section is correct.

The other approach (which we will call the brute-force approach) is to produce a beam of radioactive heavy ions to be focused onto a target of hydrogen or ^{4}He (or in a few cases to do measurements on a radioactive target[12]). The radioactive ion-beam brute-force approach is much more difficult but may provide more information. Since we have been involved in a modest effort to develop this technology along with a number of other labs[12], we make a few remarks to update the reader as to the current state of the art of our work at LLNL.

The QSBTS

In our efforts to develop this brute-force technology at LLNL our emphasis has been on simplicity and economy. The quadrupole-sextuplet beam-transport system (QSBTS) shown in Fig. 2 reflects this. A heavy-ion beam from the LLNL tandem Van de Graaff impinges on a thin primary target foil of polypropylene, polyethylene or deuterated polyethylene. A secondary beam of heavy recoils from the (p,n) or (d,n) reactions is then focused in the QSBTS. Most of the incident primary beam impinges on a centrally placed split Farady cup which is used to monitor beam position and intensity. Recoil products in the angular range of 1 to 4 degrees are accepted by the spectrometer. Since the (p,n) and (d,n) recoils have a broader angular distribution than the elastically scattered primary beam, the best compromise between beam intensity and purity can be achieved by adjusting the location of the beam stop for each reaction and energy. Figure 3 gives an example of a nearly pure ^{7}Be beam at 14 MeV produced by the ^{1}H(^{7}Li,^{7}Be)n reaction at 18 MeV. The ratio of ^{7}Be to ^{7}Li in the

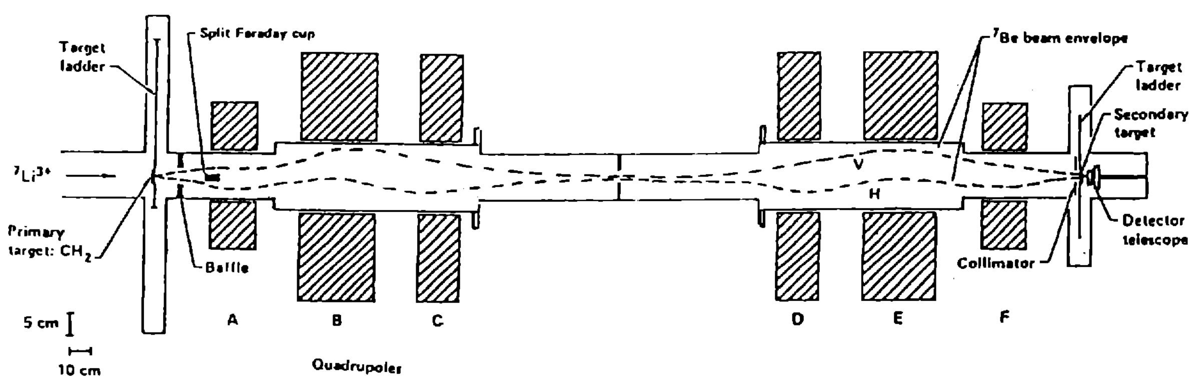


Figure 2 The present configuration of our quadrupole sextuplet beam transport system (QSBTS). By demanding a focus at the center, the background is significantly reduced.

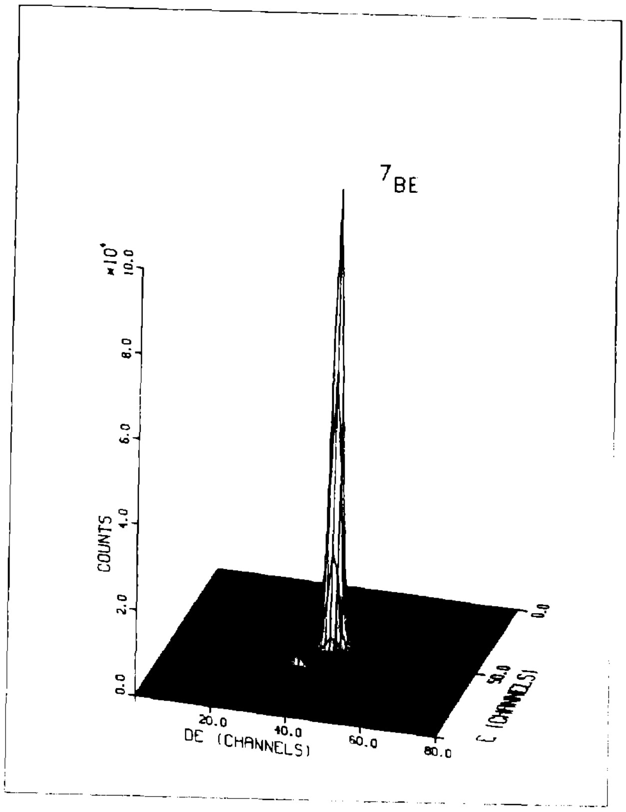
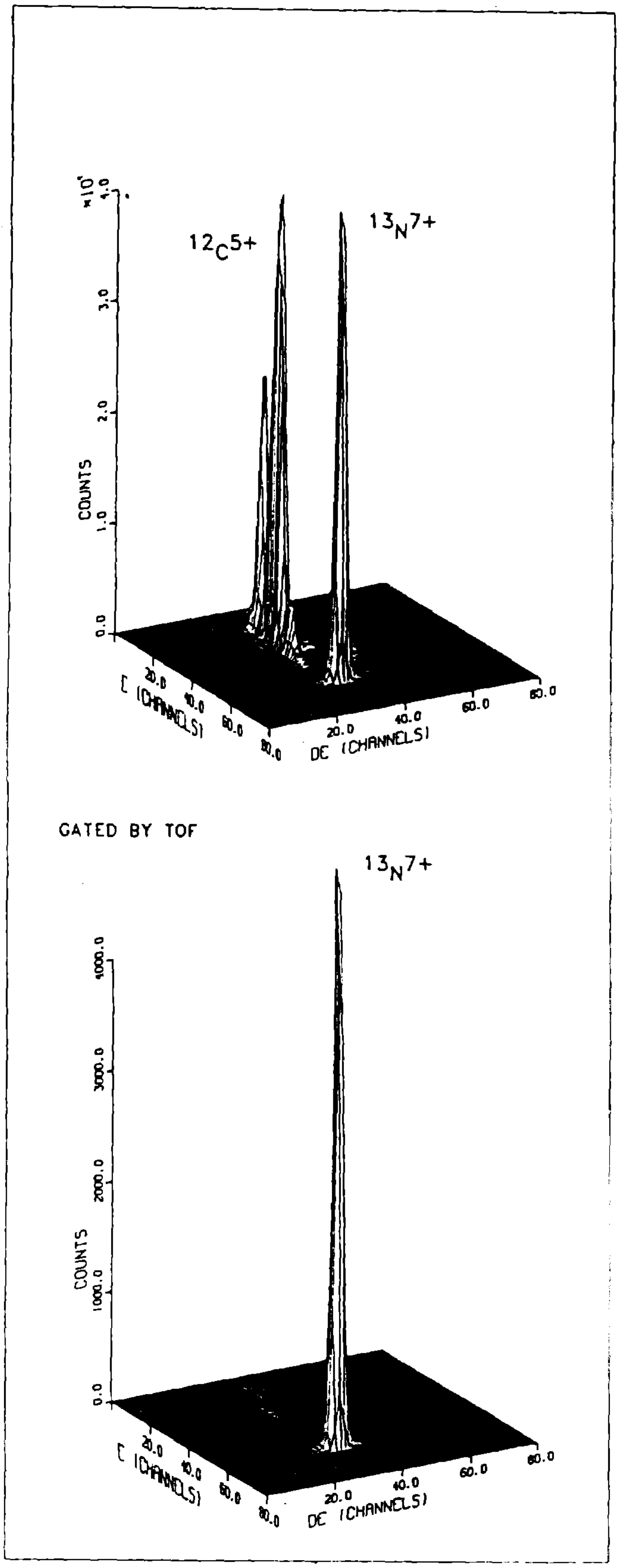


Figure 3 ΔE vs. E contours showing the profile of a 14-MeV ^{7}Be beam produced by the $^{1}H(^{7}Li,^{7}Be)n$ reaction in the QSBTS (Fig. 2).

secondary beam is about 20/1. For this run the beam stop was placed 10 cm downstream from the primary target. The conversion efficiency of incident primary beam to secondary beam through the spectrometer was about 10^{-7}.

<u>The Well-Tempered Radioactive Ion Beam</u>

Trying to do experiments with radioactive ion beams is like trying to play a Bach fugue for the first time. It begins so simply that almost anyone can do it, but soon becomes very difficult. Although the art for measuring reaction rates with radioactive ion beams has been under development for some time[13,14], progress has been slow. The main problems are fundamental. The (p,γ) cross sections of interest for astrophysics involve electromagnetic transitions and are therefore very small (typically $\lesssim 1$ nb at energies of interest away from a resonance). A second limitation is the high stopping power for the secondary heavy-ion beam in any target material. This means that even in a "thick target measurement" typically only at most a few hundred $\mu g cm^{-2}$ of target material are available for reactions in the energy region of interest. The combination of these two effects typically leads to a reduction in intensity from secondary beam to final tertiary products of about 10^{-10}. Thus, in addition to the problems of



producing, isolating, and focusing a beam of radioactive ions onto a target, one has the problem of extremely low data rates which are easily swamped by the most innocuous of backgrounds.

Figure 4 illustrates a ^{13}N beam produced in the QSBTS. The upper part of the figure shows the beam as produced in the spectrometer. It is excessively contaminated with inelastically scattered ^{12}C. However, by demanding that only events with a time-of-flight corresponding to mass 13 are counted, a reasonably well isolated beam can be obtained as shown in the lower part of Fig. 4. Nevertheless, even after nine orders of magnitude reduction of the primary ^{12}C beam, the background due to ^{16}O (produced by secondary reactions of the primary beam) still overwhelms any ^{14}O produced by the $^{13}N(p,\gamma)^{14}O$ reaction by three orders of magnitude.

Figure 4 ΔE vs. E contours showing the profile of a ^{13}N beam produced by the $^{2}H(^{12}C,n)^{13}N$ reaction in our QSBTS (Fig. 2). The upper figure is the actual beam. The lower figure shows the beam profile after time-of-flight (TOF) discrimination through the spectrometer.

Our most recent efforts at Livermore have been to reconfigure the QSBTS to best reduce the background. One improvement has been the separation of the quadrupole triplets so that a focus can be achieved through an aperature in the center (see Fig. 2). This significantly reduces the background from inelastic primary beam and allows for a longer flight path. In future runs we will bend the spectrometer at the center and insert an electrostatic deflector. In this way we should achieve both electric and magnetic filtering of the secondary beam.

Another aspect of these measurements which can and should be exploited for the purposes of background reduction is the detection of more than one signal from an event; for example, the detection of the gamma-ray as well as the recoil product. As an illustration, consider the $^{7}Be(p,\gamma)^{8}B$ reaction (or more appropriately $^{1}H(^{7}Be,^{8}B)\gamma$) which we are attempting to measure. This reaction has the useful property that the recoiling ^{8}B beta decays with a half life of 770 msec into ^{8}Be which can be detected as two alpha particles. The detection of these alpha particles when the beam is off can be exploited[15] for the measurement of this cross section. At first sight this seems like a straightforward way to eliminate the background. To our surprise, however, when we removed the secondary target from the beam we found that we could still detect alpha particles. The problem was explained when we put a deuterated polyethylene target in the primary position. The detector lit up with alpha particles. ^{8}Li produced by the $^{7}Li(d,p)^{8}Li$ reaction produces nearly the same alpha particle spectrum as that from ^{8}B. At the level of the natural abundance of ^{2}H in our primary $(CH_2)_n$ target, the ^{8}Li background overwhelms the count rate due to ^{8}B by three orders of magnitude.

To avoid this problem one must have even further redundant signatures for a valid event. Figures 5a and b illustrates an application of such redundant information in a recent measurement which we have made of the similar reaction $^{7}Be(d,n)^{8}B$. The cross section for this reaction is much larger than the $^{7}Be(p,\gamma)^{8}B$ cross section and, therefore, is a convenient test for the more difficult (p,γ) reaction. Figure 5a shows the alpha particles counted in coincidence with events which appeared in the region of the ΔE-E plane corresponding to Boron ions. Figure 5b shows the events detected with an equivalent number of random gates not in coincidence with a boron event. By subtracting the background events (and correcting for dead time while the beam is being swept off) we are able to deduce a cross section of 74±28 mb for this reaction in the energy range from 11 to 14 MeV (E_{cm} = 2.4-3.1 MeV). This is consistent with our earlier measurement[14] of this reaction at higher energy.

We intend to apply a similar technique to measure the $^{7}Be(p,\gamma)^{8}B$ reaction. In this case the coincident signitures will have to be the capture gamma ray followed by the two alpha particles in conincidence with the pair of 511 keV gamma-rays from the positron emitted in the ^{8}B decay. The annihilation radiation should allow for an adequate discrimination between the ^{8}B and ^{8}Li decays, since the latter decay does not produce a positron.

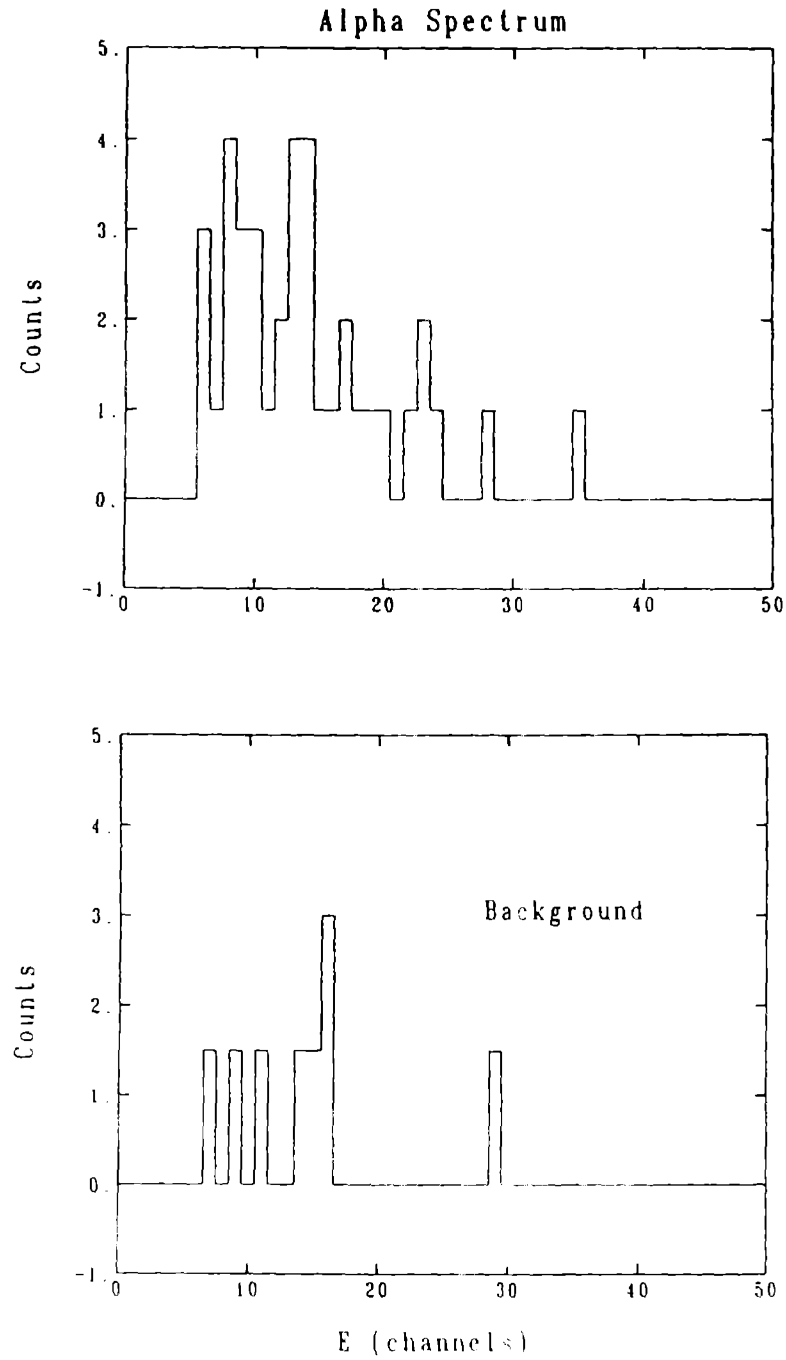


Figure 5 a) Alpha-particle spectrum in coincidence with Boron-like events in the ΔE-E plane from the $^7Be(d,n)^8B$ reaction; b) Normalized alpha-particle spectrum from an equivalent number of random samples as in a). This spectrum constitutes a measurement of the background from the $^7Be(d,n)^8B$ reaction.

CONCLUSION

Clearly, the problem of the further development of this technology is a formidable one. Nevertheless, the technology has been proven to work for the measurement of at least some cross sections[14], and considerable further reductions in background can be envisioned with existing technology. One of the most promising possibilities is the acceleration of the beam of interest directly from the ion source. Proposals of this type have been suggested at Berkeley[12] and TRIUMF[16]. If sufficiently developed, this approach may best surmount the background problem.

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